BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

68 11044

SUBJECT: CSM Attitude Control for Lunar Orbital Experiments - Case 340

DATE: November 15, 1968

FROM: A. W. Zachar

ABSTRACT

A lunar remote sensing experiments program has been initiated. Its purpose is to obtain information about the Moon from lunar orbit. Implementation of this program requires support from the CSM.

The ability of the CSM to provide this support has been partially investigated. The results indicate that the spacecraft is mechanically capable of performing the attitude maneuvers required for proper orientation of the various experiments. Automatic command of these maneuvers is not, however, possible without modification of the existing automatic control equipment. Manual command appears to be feasible.

The impact of CSM support of the remote sensing experiments on the RCS fuel budget does not seem to be excessive. Fuel usage is, in fact, quite small when compared to the unused but available SM RCS fuel associated with a LM rescue mission.

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MEMORANDUM FOR FILE

1.0 INTRODUCTION

A lunar remote sensing experiments program has been initiated. Its purpose is to obtain information about the Moon from lunar orbit. During the early manned lunar missions, this remote sensing will be restricted to photographic experiments executed from the Command Module. The later lunar missions, in support of remote sensing, will employ various experiments located in sector I of the Service Module. In both cases, experiment execution will require that the CSM be capable of performing certain attitude maneuvers. Insufficient knowledge of RCS requirements and capabilities with respect to these attitude maneuvers has prompted the following study.

2.0 DISCUSSION

The types of experiments and their execution have been considered on two levels; those associated with the first few lunar landings and any prior flight test missions in lunar orbit and those associated with the follow-on landing missions. The early mission experiments will most likely be photographic experiments executed from the CM using the SM RCS to satisfy pointing requirements. The follow-on landing missions will be concerned with experiment packages consisting of various experiments and located in sector I of the SM. Pointing requirements will again be satisfied through use of the SM RCS with, perhaps, some pointing capability incorporated in the experiments package itself.

2.1 Attitude Control Requirements for Orbital Science

The first part of this study is concerned with the attitude maneuvers required of the CSM by the various experiments. It was assumed, for these calculations, that the experiments package has no pointing capabilities.

The CSM required attitude maneuvers comprise both orientation and attitude rate. The CSM orientation is a function of, among other things, the particular experiment being performed. Thus, for the photographic experiments scheduled to be performed from the CM, the window through which the camera is to be pointed dictates the CSM orientation. With the experiments package located in sector I of the SM, the spacecraft orientation will most likely be with the x-axis parallel to the lunar surface; see Figure 1.

A specific attitude rate of the CSM is needed to provide image motion compensation (IMC) when this corrective factor is not provided for by the experiments package. From a 60 n.m. circular orbit, for example, a CSM attitude rate of .84 deg/sec provides IMC; that is, an arbitrary axis is kept pointed to a particular point on the lunar surface. The tolerance on this attitude rate depends on the experiment being performed. With respect to the photographic experiment, for example, an allowable smear of two meters coupled with a .01 second exposure time results in a $\pm$ .1 deg/sec tolerance.* This tolerance is inversely proportional to the exposure time. Thus, the required CSM attitude rate for this particular experiment may be written $\omega = .84 \pm .1$ deg/sec.

2.2 Present CSM Attitude Control Capability

The second part of this study is concerned with the ability of the CSM to perform the required attitude maneuvers. This maneuver ability has been considered on the basis of maneuver producing and maneuver control capabilities.

CSM attitude maneuvers are accomplished using the SM RCS. The ability of the RCS thrusters to provide the required attitude and attitude rates has been investigated. It was found that normal two jet minimum impulse firing of the SM RCS rockets imparts a .0177 deg/sec attitude rate about an axis possessing a 50,000 slug ft^2 mass moment of inertia; (I_{xx} = 18,390 slug ft^2, ω = .0482 deg/sec as of May 1968). This minimum attitude rate may be further reduced by firing only one RCS thruster; the associated spacecraft translation is negligible.

Consider next the methods available for commanding CSM attitude and attitude rate. There are two basic command modes, manual and automatic.

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*See Appendix A.

The manual command mode permits the astronaut to "fly" the spacecraft. CSM translation and rotation maneuvers are commanded by the astronaut using hand controls located on the left and right hand crew couches. The maneuver rate is a function of hand control deflection. In addition, the astronaut is able to select a minimum impulse mode whereby a small deflection of the hand control fires the RCS thrusters for .014 seconds. A minimum impulse attitude control device is also located in the vicinity of the sextant station.

Automatic attitude control of the CSM is achieved using either the primary (Guidance, Navigation, and Control, GN&C, or PGNCS) or the secondary (Stabilization and Control Subsystem, SCS) control system. Using the GN&C, the astronaut is able to select discrete maneuver rates of .05, .2, .5, and 4.0 degrees/second.[1] This system also provides attitude hold with a deadband range of .5 to 5.0 degrees. The SCS permits selection of discrete maneuver rates of .7 deg/sec in pitch, yaw, and roll and 7.0 deg/sec in pitch and yaw and 20.0 deg/sec in roll. All SCS maneuver rates have a possible error of ± 20%. Attitude hold deadband is .2 to 4.2 degrees.

2.3 Methods for Satisfying Attitude Maneuver Requirements

With this information in mind, we consider several candidate techniques for CSM support of remote sensing experiments. The discussion is directed to high resolution photography but applies also to other remote sensing experiments.

We wish to minimize the impact of the remote sensing experiments on astronaut time. Thus, automatic execution of the various experiments is desirable. Unfortunately, it is not possible to automatically obtain the maneuver rate required for IMC from a 60 n.m. circular orbit without altering the existing equipment. Possible equipment alterations include a hardware change such that the selectable discrete maneuver rates of the GN&C system would be .05, .2, .5, .84, and 4.0 deg/sec. A software change has also been considered. It is noted, however, that any on-board computer program change requires reverification of all other existing programs because of computer storage problems. Therefore, a software change is unlikely for the early missions. As a consequence, it appears that, at least for the early lunar missions, automatic maneuver rate selection for 60 n.m. orbit IMC is not likely.

If absolutely necessary, an orbit altitude change to approximately 12.9 n.m. could be accomplished such that the 4.0 deg/sec maneuver rate automatically available in the GN&C system could be used to provide IMC. Raising the orbital altitude to 98.9 n.m. would permit use of the .5 deg/sec maneuver rate to compensate for motion but at a sacrifice in areal resolution.

Another method of CSM support of the remote sensing experiments and, in particular, high resolution photography makes use of a combination of both automatic and manual attitude control. Consider the sequence of events as depicted in Figure 2.

The spacecraft is commanded via the GN&C to assume the attitude as shown at point A and to hold this attitude until reaching point B. At this time, it is taken off attitude hold and the RCS jets are manually fired until an attitude rate of approximately .84 deg/sec is achieved. Attainment of this attitude rate may be checked on the attitude rate indicator which has a minimum full scale deflection of 1.0 deg/sec. The proper execution of these events should result in the camera optical axis being pointed in the vicinity of the target and possessing reasonably good IMC. Additional adjustments to the spacecraft attitude and attitude rate are required to compensate for various errors; for example, uncertainties in the selenographic coordinates. Another error source is related to the changing IMC attitude rate with angular displacement from the target. That is, the required attitude rate for IMC increases as the angle between the line of sight to the target and the flight path increases. If, for example, the CSM achieved exactly the over-the-target IMC rate (.842 deg/sec) 30 seconds too soon, the absence of further attitude rate adjustments would result in the camera being pointed to a spot on the lunar surface located some 2.6 km from the target; see Figure 3.

Fine tuning of the spacecraft (camera optical axis) attitude and attitude rate can be manually accomplished by the astronaut using the RCS minimum impulse mode while sighting the target, most likely through the optical system of a reflex camera. A possible equipment arrangement would have the camera mounted on the crew hatch window with the RCS rotational hand control fixed to the center aisle arm of either the left or right hand crew couch. It is noted that the RCS hand controls may be mounted on either arm of the left and right hand crew couches and that they remain functional even when mechanically disconnected from them. They are attached to a nine foot signal transmitting cable.

Point C of Figure 2 shows the spacecraft in position for photographing the target. Theoretically it should have the correct attitude and attitude rate for target acquisition and IMC. In support of this technique, we recall that the required attitude rate for IMC under the conditions previously described is $\omega = .84 \pm .1$ deg/sec and note that the astronauts are, in general, currently achieving a simulated attitude rate of approximately .05 deg/sec through manual use of the RCS minimum impulse mode.

A method for obtaining a series of overlapping photographs once the initial photograph has been taken is now presented. We propose that the camera mounting bracket contain a provision for swinging the camera through an arc in discrete and equal steps. The effect of such a device is as shown in Figure 4.

At point C the camera optical axis is presumed to be pointed at target 1 and to have the correct attitude rate for IMC. This attitude rate will keep the camera pointing to target 1 until point D is reached. At this time, the camera is swung through a predetermined arc so that it now points to target 2. This procedure is repeated for the remaining targets. We note that IMC is maintained for all targets without additional expenditure of RCS fuel. The effects of the window field of view and the changing relationship between the windowpane and the camera optical axis would have to be assessed.

The taking of multiple overlapping photographs relaxes somewhat the required pointing accuracy of the initial photograph. That is, it would be acceptable if the target appeared in photographs three or four rather than in the first photograph.

2.4 Remote Sensing Impact on RCS Fuel Reserves

An investigation has been made of the SM RCS fuel budget and its ability to support the remote sensing experiments program. A graph of SM RCS fuel usage is presented in Figure 5.[2] Referring to Figure 2, the maximum amount of RCS fuel required to obtain attitude A is .6 lbs at .2 deg/sec and 1.88 lbs at .5 deg/sec; see Figure 6. This assumes that the mass moment of inertia is 59,780 slug ft^2 (the maximum I as of June 1968) about the axis of rotation. For a rotation of 180°, the times required for this maneuver are 15 and 6 minutes respectively, (does not include dynamic disturbances).

The spacecraft is then placed in the .5° attitude hold mode until reaching point B. This requires a maximum of .05 lbs of fuel. At point B, the craft is taken off attitude hold and given an impulse necessary to produce a .84 deg/sec angular velocity. Approximately 2.0 lbs of fuel is used. After this maneuver, the spacecraft is placed in a drifting mode and fine tuning is accomplished using the RCS minimum impulse mode. Fuel usage during this phase should be negligible. Therefore, the maximum amount of RCS fuel required to orient the CSM and provide IMC for a high resolution photograph is 3.9 lbs. This is to be compared with the 230 lbs of usable SM RCS fuel available at the end of a mission during which a LM rescue has been performed; see Figure 5. It is also interesting to observe that, using the PGNCS, .5 degree attitude hold about all three axes requires approximately 1 lb of SM RCS fuel per lunar orbit; see Figure 6.

A high resolution photograph of a second target can be obtained in several ways; for example, the camera swing technique previously described. If, however, the second target is beyond the range of the maximum angular displacement of the camera optical axis or if the camera is rigidly fixed to the spacecraft, camera orientation for photographing the second target must be accomplished via CSM attitude maneuvers. Assuming that the CSM has the proper attitude and attitude rate for photographing the first target, the proper CSM attitude mode for photographing the second target can be obtained in two ways. One, the spacecraft can be required to perform a 360° attitude maneuver at a rate related to the distance between the targets and then given the IMC attitude rate when it is over the second target; or two, the spacecraft attitude rate can be reduced from IMC to orbital and then increased to IMC when it is over the second target. These maneuvers consume the same amount of RCS fuel when the two targets are displaced approximately 11.5 degrees lunar central angle. For the second target displaced approximately 23 degrees lunar central angle from the first, no additional RCS fuel is required; see Figure 7.

Another factor affecting the RCS fuel budget in support of remote sensing experiments is the CSM lunar orbit orientation constraints and associated opportunities for experiment execution. The thermal constraints require that the CSM be oriented in lunar orbit such that the perpendicular to the equivalent surface area of the Environmental Control Subsystem (ECS) radiators lies beyond 25° to the local vertical whenever the CSM is within 25° of the subsolar point; see Figure 8.[3] This constraint may be violated for no more than three consecutive orbits and for no more than a total of eight orbits. The communications constraints are presented in Figures 9 and 10.[1] The degree to which all of these constraints will be observed has not been firmly established.

Another constraint on the CSM is the need to perform landmark sightings. The possibility of obtaining high resolution photographs from the sextant station during these periods has been considered. The advantage, of course, is that this technique places no additional requirements on the RCS fuel budget. However, the mounting of the camera poses a problem in that there is no window at the sextant station through which a camera might be pointed. Use of the sextant optical system for this purpose is currently being pursued at MSC; the use of an adapter to permit the mounting of a sequence camera on the sextant is planned for Mission C'. Unfortunately, the astronaut will not be able to view the target through this optical system. If on the other hamd, a reflex camera were mounted, fine tuning of the spacecraft could be manually achieved using the minimum impulse control located near the sextant station.

3.0 CONCLUSIONS

The ability of the CSM to support lunar remote sensing experiments has been investigated. It has been found that, most likely, the spacecraft is mechanically capable of performing the required attitude maneuvers. Automatic command of these maneuvers is not, however, possible without modification of the existing automatic control equipment. Manual command appears to be feasible.

The impact of CSM support of the remote sensing experiments on the RCS fuel budget does not seem to be excessive and is, in fact, quite small when compared to the unused but available SM RCS fuel associated with a LM rescue mission.

2015-AWZ-acm

A. W. Zachar

Attachments
- References
- Figures 1-10
- Appendix A

REFERENCES

1. "CSM/LM Spacecraft Operational Data Book", Vol. 1, SNA-8-D-027, May 1968.

2. "The Lunar Landing Mission SMRCS Propellant Budget as Defined for the Configuration Control Board", MSC Internal Note No. 67-FM-171, November 13, 1967.

3. "Mission Modular Data Book", SID 66-1245, January 1967.

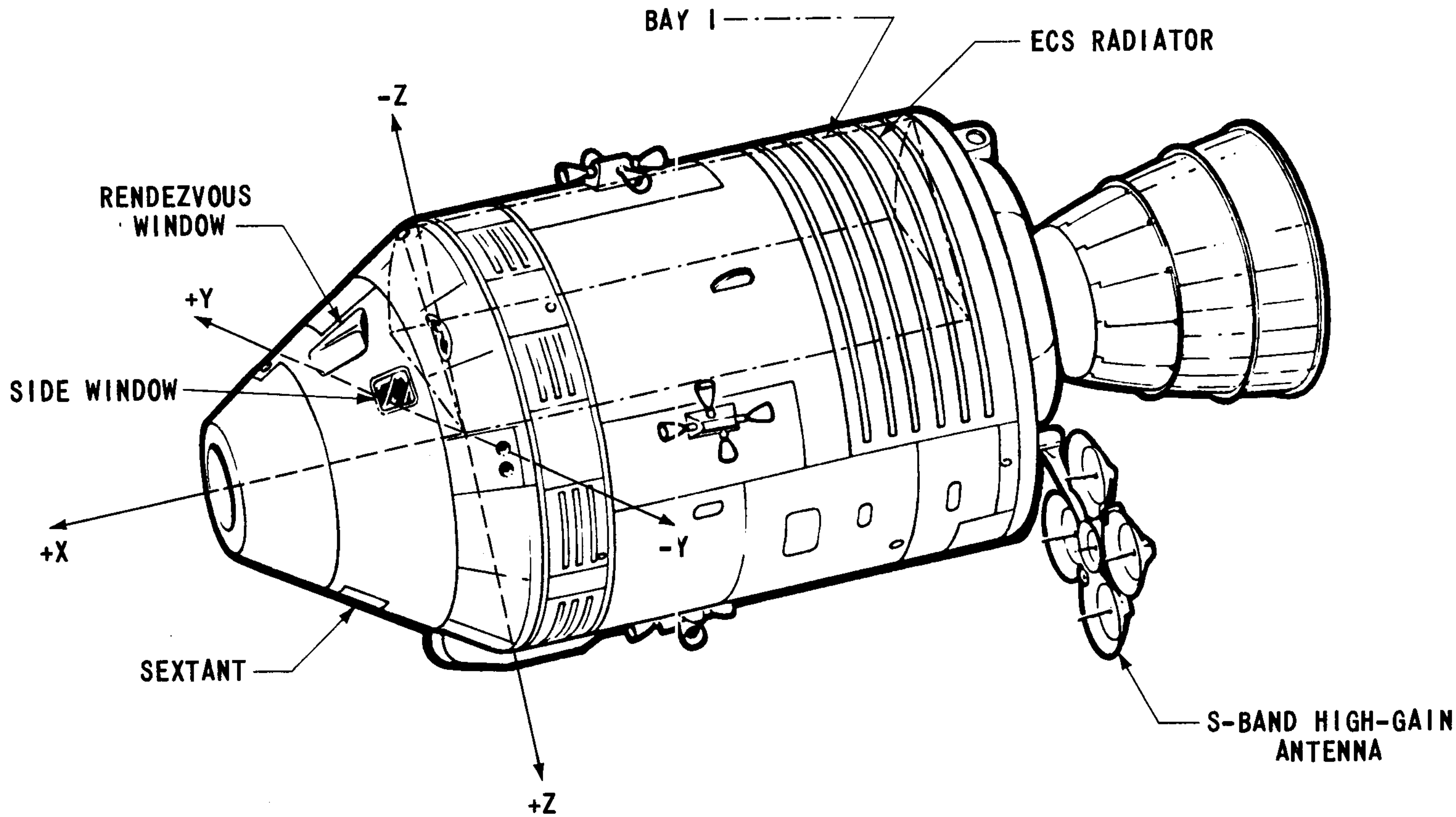


FIGURE I - COMMAND & SERVICE MODULE

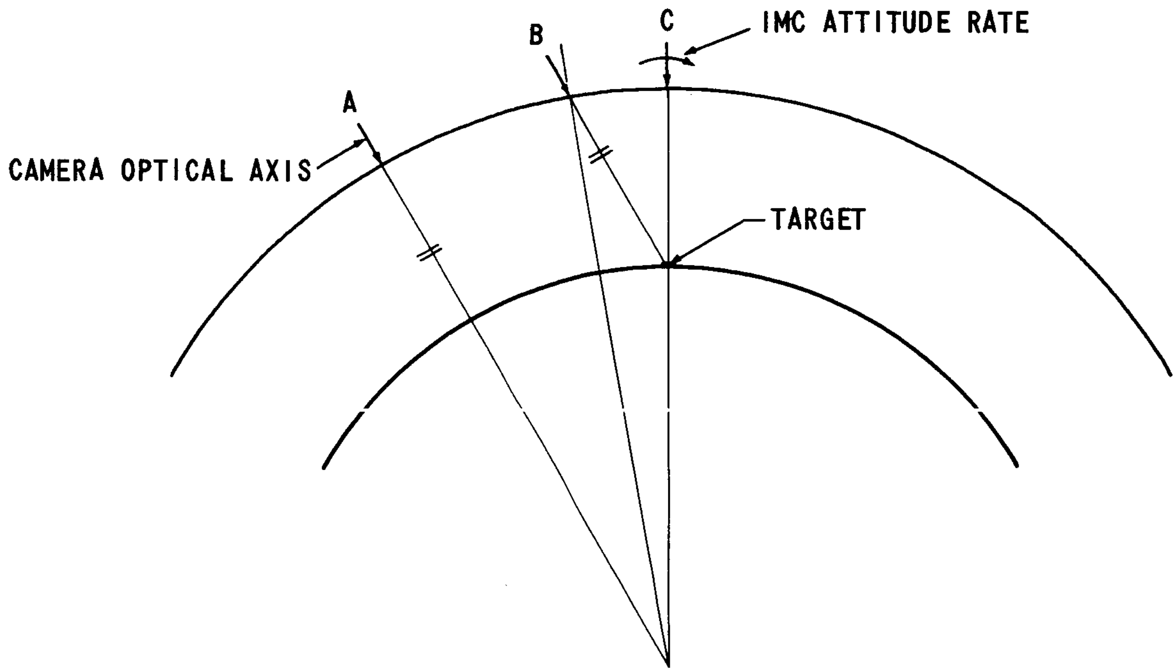


FIGURE 2

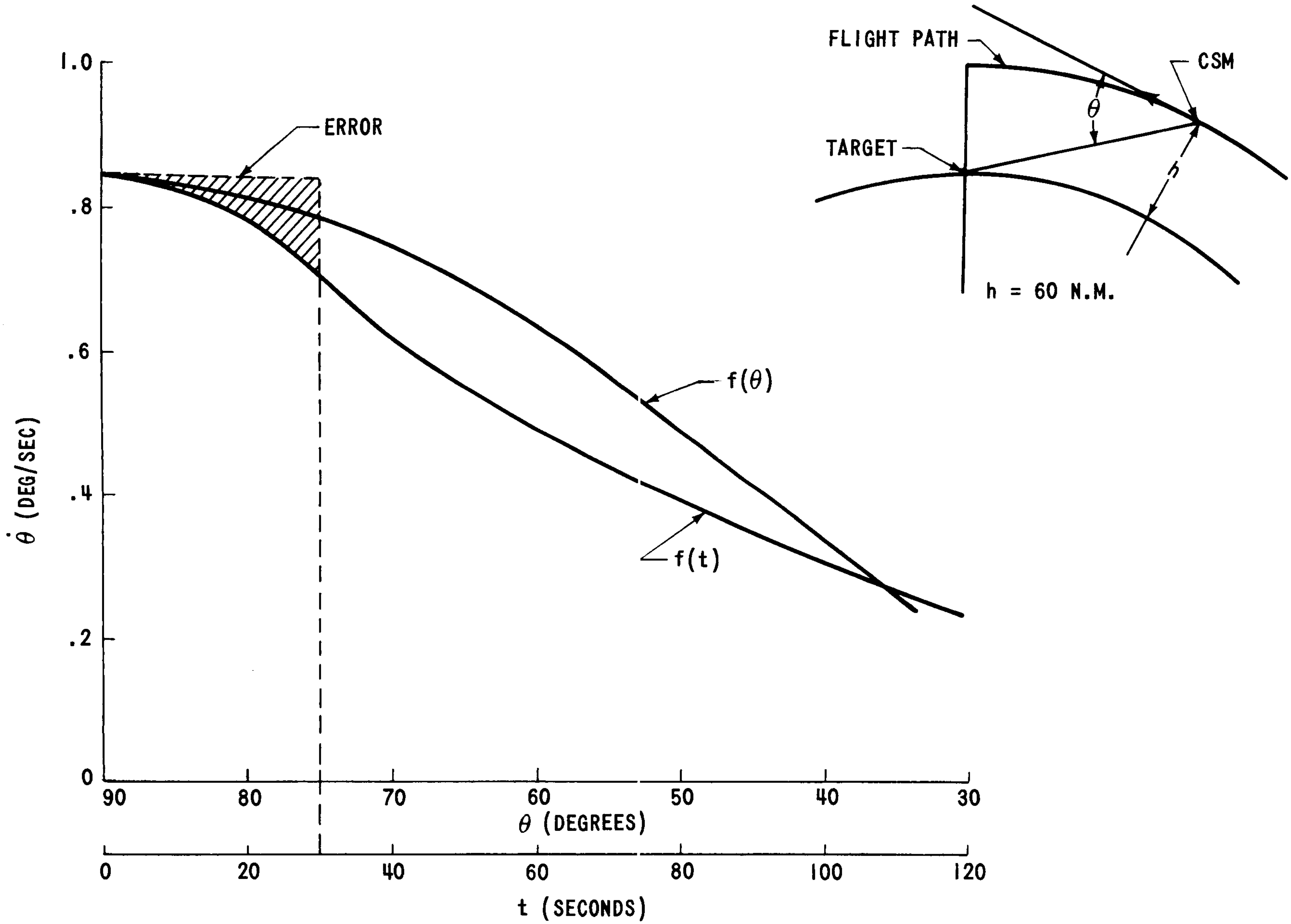


FIGURE 3 - $\dot{\theta}$ vs θ AND t

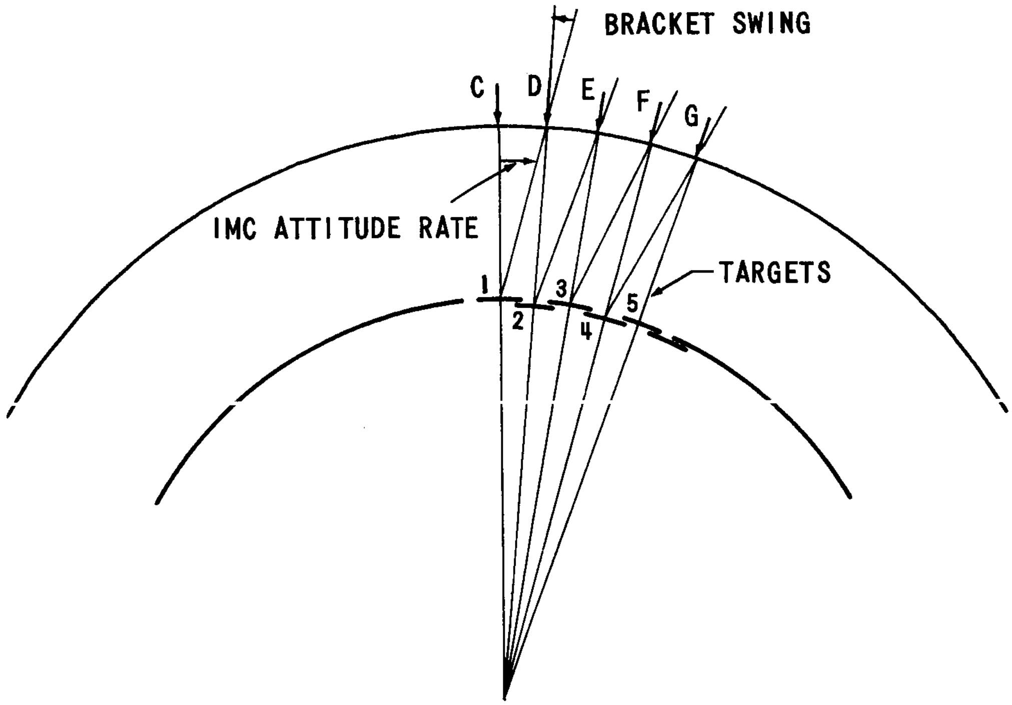


FIGURE 4

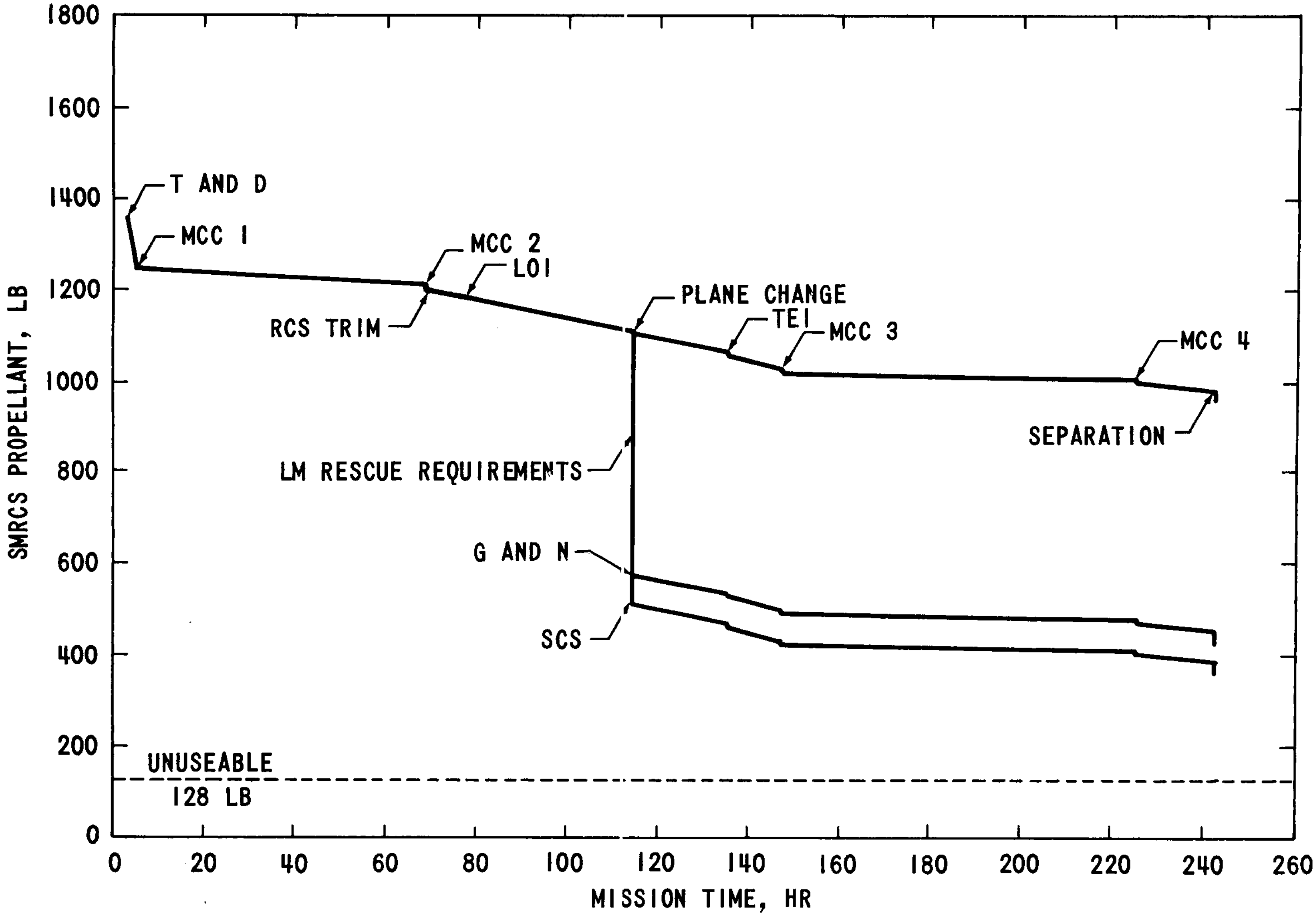
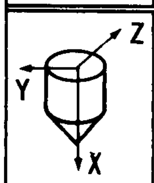
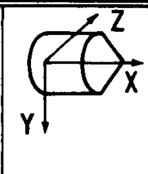
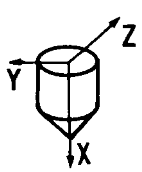
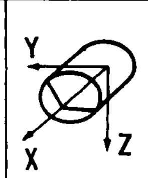
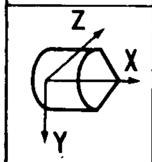
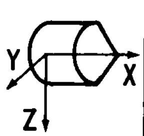


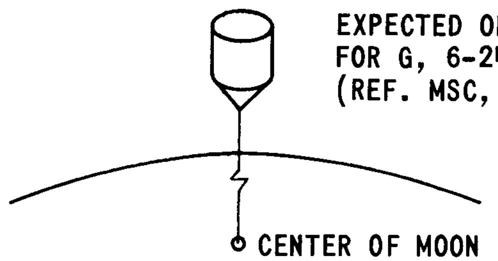
FIGURE 5 - LUNAR LANDING MISSION SMRCS PROPELLANT UTILIZATION

CSM ATTITUDE EXPENDITURES WHILE IN LUNAR ORBIT - MISSION "G" (WITHOUT LM)

INITIAL POSITION	FINAL POSITION	MANEUVER	@ $\Delta\omega$ = .2 DEG/SEC FUEL CONSUMED	@ $\Delta\omega$ = .2 DEG/SEC ELAPSED TIME	@ $\Delta\omega$ = .5 DEG/SEC FUEL CONSUMED	@ $\Delta\omega$ = .5 DEG/SEC ELAPSED TIME	ATTITUDE HOLD .5 DEGREE
		YAW 90°	.6 LBS.*	7.5 MIN.	1.88 LBS.*	3 MIN.	.09 LBS./HR.*
		PITCH 90°	.58 LBS.*	7.5 MIN.	1.80 LBS.*	3 MIN	.1 LBS./HR.*
		ROLL 90°	.2 LBS.*	7.5 MIN.	.88 LBS.*	3 MIN.	.32 LBS/HR.*

*REF. CSM DATA BK., VOL. I, MAY '68.
(PGNCS, DOES NOT INCLUDE DYNAMIC DISTURBANCES)

I_{xx} = 18,392 SLUG. FT.^{2}
I_{yy} = 54,330 SLUG. FT.^{2}
I_{zz} = 59,780 SLUG. FT.^{2} (REF. MSC, SAM KAMEN, 6-18-68)
WT. = 35,300 LBS.



EXPECTED ORIENTATION
FOR G, 6-24-68
(REF. MSC, J. LOWERY)

FIGURE 6

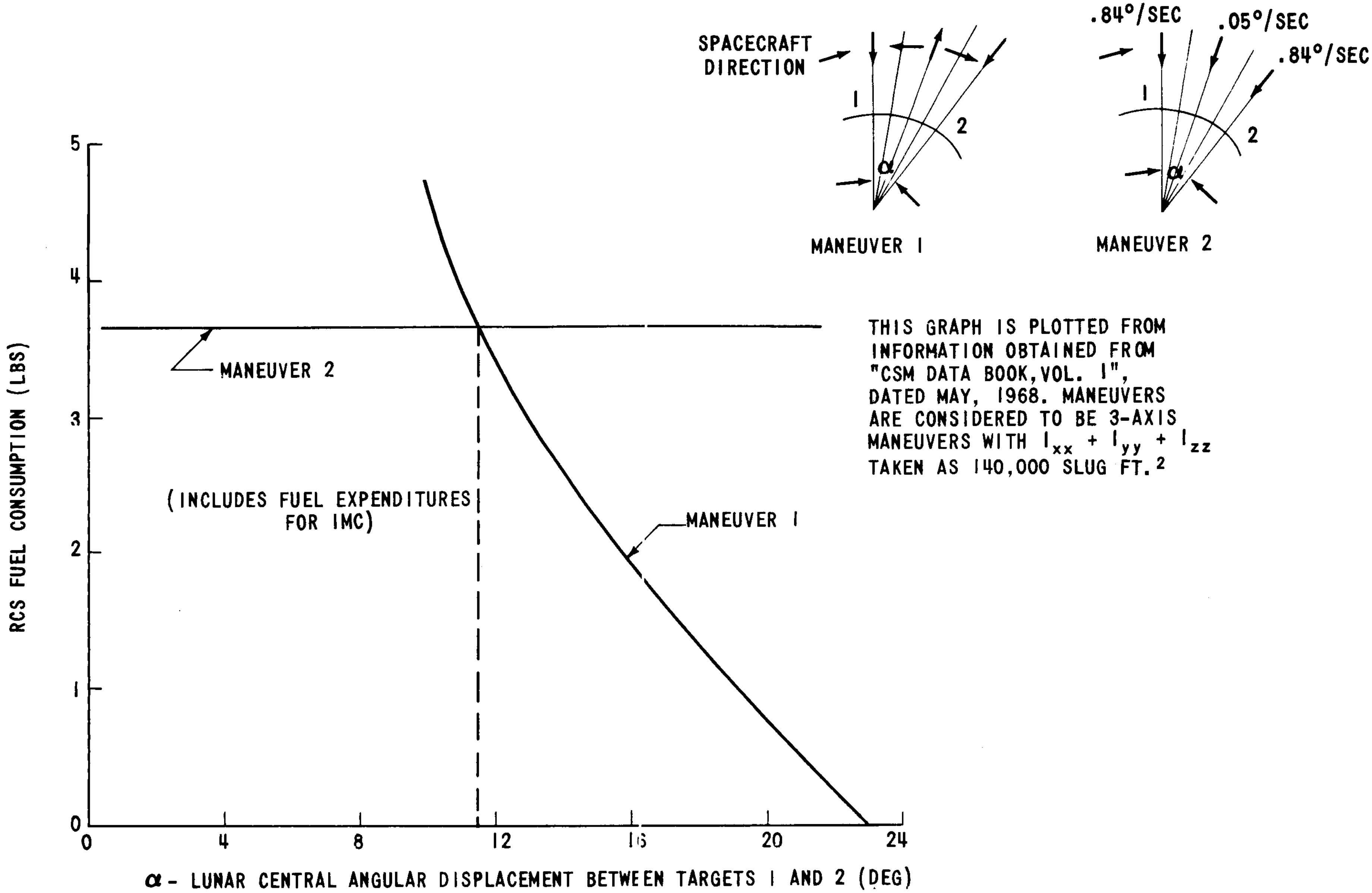
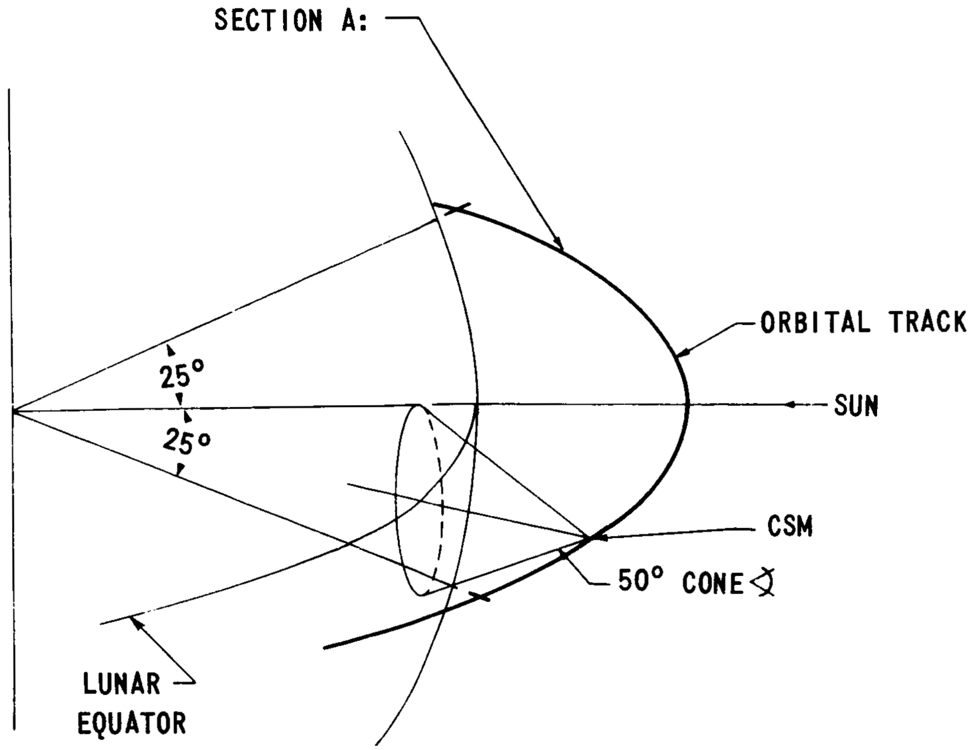

SPACECRAFT DIRECTION
MANEUVER 1
.84°/SEC
.05°/SEC
.84°/SEC
MANEUVER 2
THIS GRAPH IS PLOTTED FROM INFORMATION OBTAINED FROM "CSM DATA BOOK, VOL. I", DATED MAY, 1968. MANEUVERS ARE CONSIDERED TO BE 3-AXIS MANEUVERS WITH $I_{xx} + I_{yy} + I_{zz}$ TAKEN AS 140,000 SLUG FT.^{2}
RCS FUEL CONSUMPTION (LBS)
MANEUVER 2
(INCLUDES FUEL EXPENDITURES FOR IMC)
MANEUVER 1
α - LUNAR CENTRAL ANGULAR DISPLACEMENT BETWEEN TARGETS 1 AND 2 (DEG)

FIGURE 7



THERMAL REQUIREMENT - ⊥ TO ECS RADIATOR (EQUIVALENT FLAT PLATE SURFACES) MUST LIE OUTSIDE OF 50° CONE WHILE CSM IS IN SECTION A, (CAN BE VIOLATED FOR NO MORE THAN 3 CONSECUTIVE ORBITS AND NO MORE THAN 8 TOTAL ORBITS). THE ECS RADIATORS EXTEND OVER BAYS II, III AND V, VI.

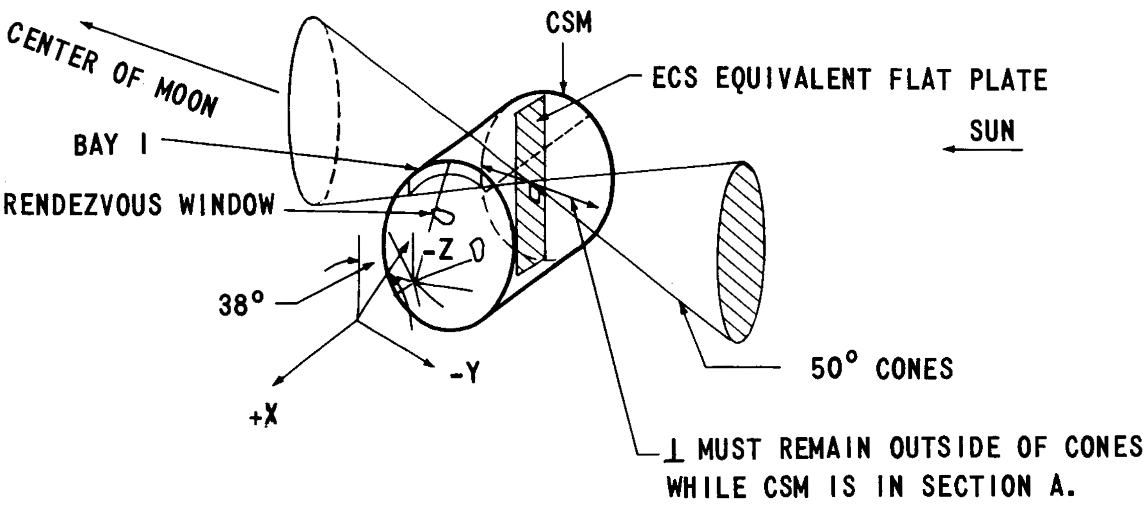


FIGURE 8

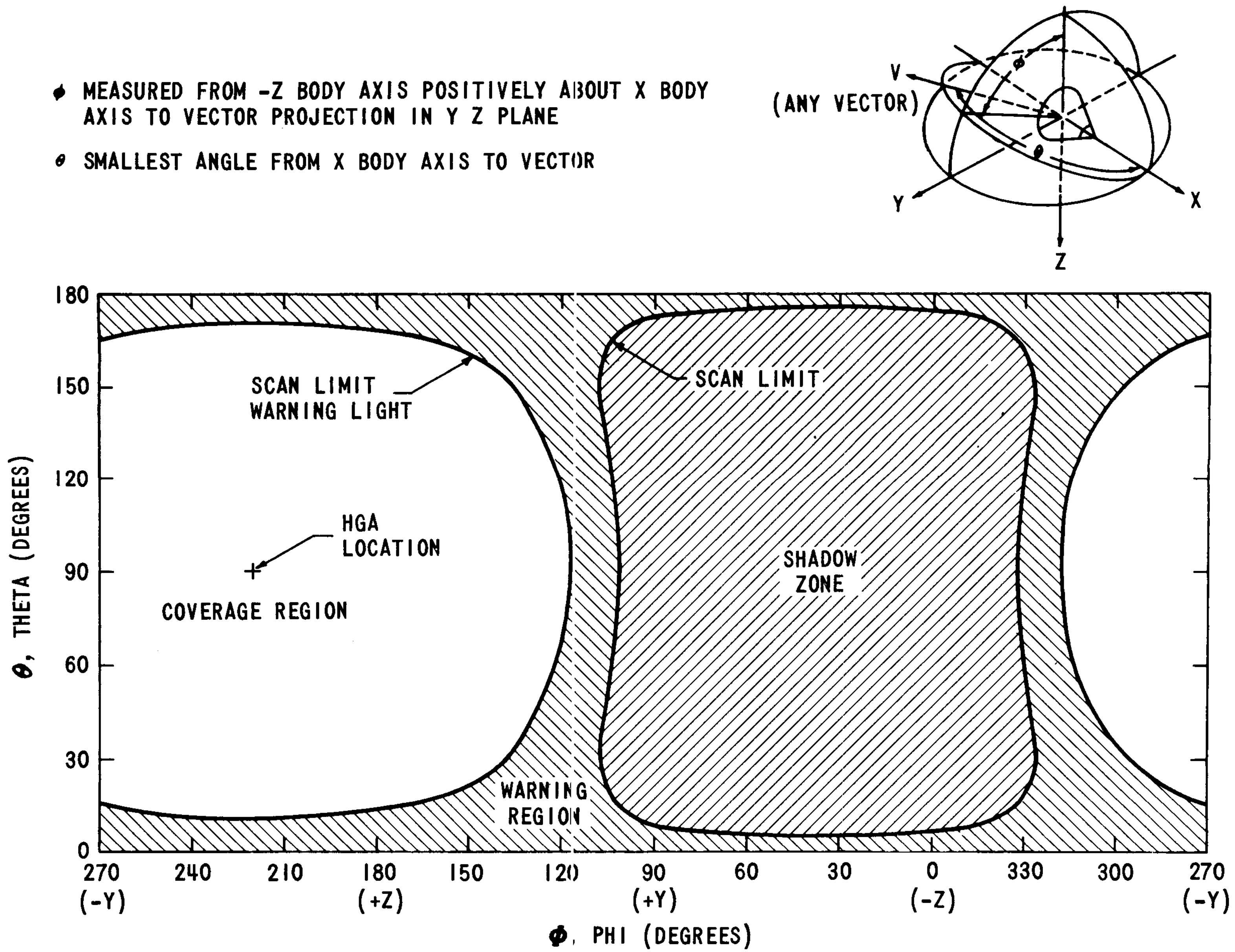


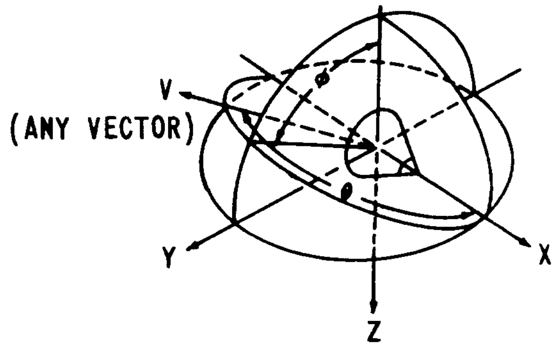
FIGURE 9 - HIGH-GAIN ANTENNA SCAN LIMIT, CSM ONLY

NOTES:

1. ALL DB FIGURES ARE BELOW THE ISOTROPIC LEVEL.
2. EXPECTED -3 DB BOUNDARIES.

ϕ MEASURED FROM -Z BODY AXIS POSITIVELY ABOUT X BODY AXIS TO VECTOR PROTECTION IN Y Z PLANE

θ SMALLEST ANGLE FROM X BODY AXIS TO VECTOR



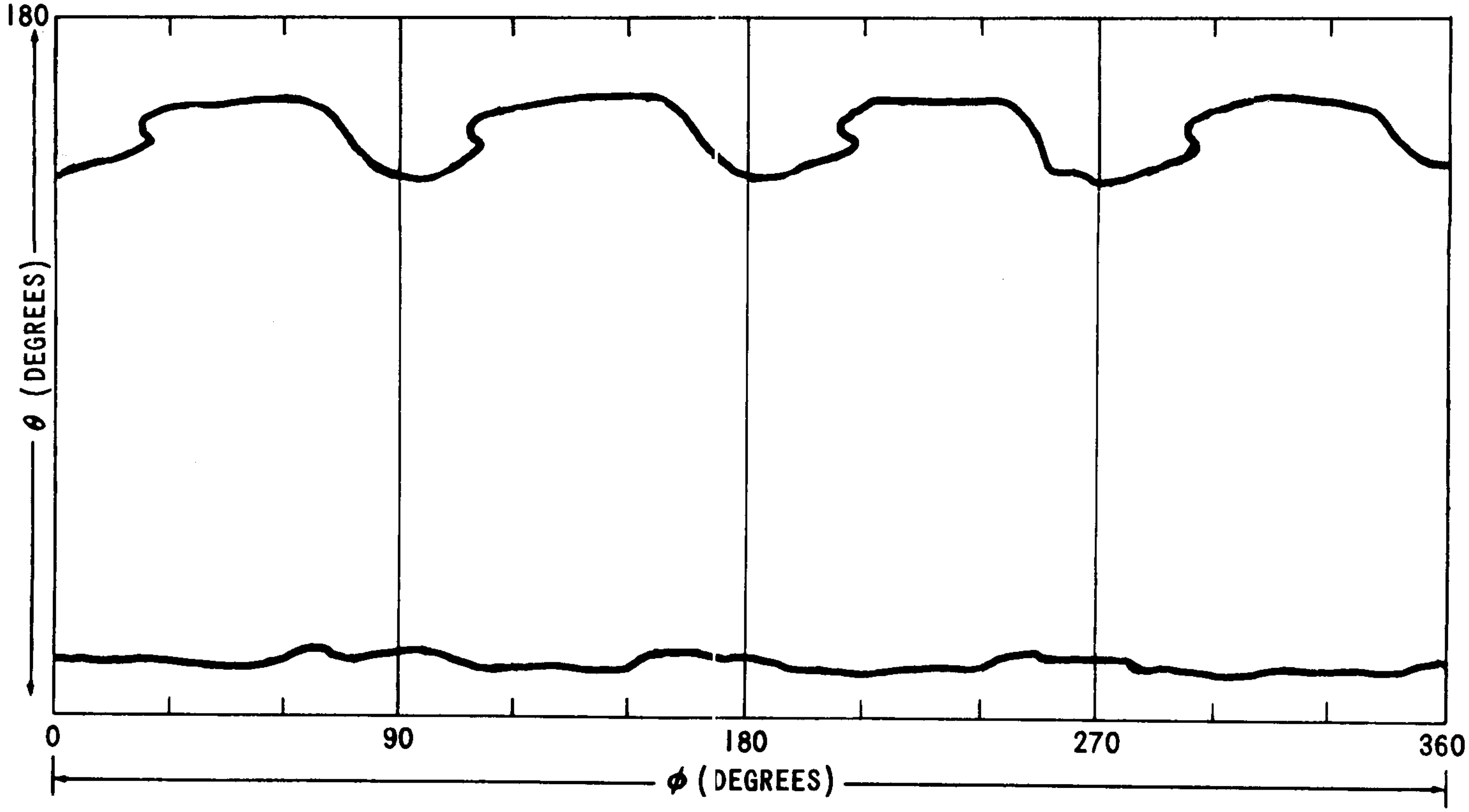


FIGURE 10 - BLOCK II S-BAND COMPOSITE PATTERNS, FOUR OMNI-ANTENNAS (CSM)

APPENDIX A

ATTITUDE RATE REQUIRED FOR IMC

From a 60 n.m. altitude, the CSM attitude rate required to keep an arbitrary axis of the CSM pointed to a particular lunar target is approximately .84 deg/sec. This rate has been computed in the following manner. At a 60 n.m. lunar altitude, the orbital velocity is 1.014 mi/sec. Thus the orbital rate is

$$\dot{\theta} = \frac{V}{h} = \frac{1.014}{69.1} \frac{\text{rad}}{\text{sec}} = .01469 \text{ rad/sec}$$

or $$\dot{\theta} = .842 \text{ deg/sec.}$$

The tolerance on $\dot{\theta}$ is approximately $\pm$ .1 deg/sec for a photographic experiment in which a 2 meter smear is allowed and the exposure time is .01 sec. This number has been obtained in the following manner. The 60 n. m. altitude is equivalent to 111,300 meters. The smear angle (θ_s) associated with a 2 meter smear is then

$$\theta_s = \frac{2}{111{,}300} = 1.79 \times 10^{-5} \text{ rad}$$

$$\theta_s = .00103 \text{ deg}$$

and for a .01 sec exposure time

$$\dot{\theta}_s = \frac{.00103}{.01} \frac{\text{deg}}{\text{sec}} = .103 \text{ deg/sec.}$$

$\therefore$ for this particular experiment, the required CSM attitude rate may be written

$$\omega \approx .84 \pm .1 \text{ deg/sec.}$$

BELLCOMM, INC.

Subject: CSM Attitude Control for Lunar Orbital Experiments

From: A. W. Zachar

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